SUSCEPTIBILITY OF LIMESTONES TO DIAGENESIS AND WEATHERING PROCESSES

Abdel-Latif A. Qahwash

Dept. of Earth Sciences, KFUPM, Dhahran 31261

ABSTRACT

Limestone is used in practice for a great number of purposes, especially in construction and chemical industry. Limestone rocks not only have complicated and varied depositional patterns, but also are subject to extensive post-depositional changes which alter their original properties. Diagenetic processes which result in porosity changes are introduced. Environmental processes which produce cavities in limestone are also discussed.

KEYWORDS

Limestone; micrite; diagenesis; neomorphism; aragonite; dolomite; porosity, strain cavities; solution cavities.

INTRODUCTION

Limestone and dolomite form a continuous series of calcium-magnesium carbonate rocks. End members consist of high-calcium limestone (greater than 95% $CaCO_3$) and high-magnesium dolomite (85 -95% $CaMg(CO_3)_2$;intermediate members consist of magnesium limestone and dolomitic limestone. The common naturally occurring carbonate minerals are: calacite ($CaCO_3$), dolomite $CaMg(CO_3)_2$, aragonite ($CaCO_3$), and Mg calcite. These minerals can occur with impurities of quartz, clay minerals, chert, gypsum, anhydrite, and pyrite. The term Mg calcite is normally referred to unstable calcite with greater than 5mol% $MgCO_3$. With time, Mg calcite loses its Mg and is converted into calcite. The amount of magnesium present in natural Mg calcite decreases with decreasing temperature, i.e. with increasing latitude and increasing ocean depth.

The carbonate minerals exist in three forms: micrite, fibreous, and coarse crystals. The general occurrences of carbonate minerals and their different forms are attributed to the effect of Mg^{+2} and Na^{+2} ions in the precipitating waters, and to the rate of crystal growth. Micrite texture is the result of rapid near-surface precipitation by organic influence, evaporation, or chemical reactions. Fibreous texture is prevalent in aragonite and Mg calcite that form at relatively low rates of crystallization. Large equant crystals of sparry calcite develop in the subsurface where rate of crystal growth is slow and the organic influence is not significant. Slow crystal growth rates also favor the growth of large dolomite crystals in the subsurface where the Mg: Ca ratio is above 1:2, Given and Wilkinson (1985).

PRINCIPAL USES

Limestone is the most important of the industrial rocks; its products range from crushed aggregates to micro-sized limestone. Crushed stone, dimension stone, and facing stone utilize the physical and mechanical properties. Whereas the chemical composition is important when limestones are principally used as a lime in cement, as flux in smelting, and as fillers in paper, plastics, and rubber. Above all is the fact that limestones and dolomites are common aquifers of goundwater and reservoirs of oil and gas. About 40% of the world's oil is produced from carbonate rocks.

OCCURRENCE

Carbonate rocks are comnonly of shallow marine origin. They may form by the accumulation of calcium carbonate-bearing shells and skeletons of marine organisms; or by the precipitation of carbonate minerals from carbonate saturated water by biochemical and physiochemical processes. The carbonate sediments tend to be cemented by calcite and/or micrite (calcareous mud). The purity (calcium carbonate content) of limestones is in general inversely proportional to the micrite content. High calcium limestone is generally associated with high energy environments that produce sand-sized carbonate grains, whereas micrite tends to accumulate in deep water environments where the associated non-carbonate silt and clay-sized particles make it less pure.

Most dolomite is secondary, resulting from the replacement of calcium in limestone by magnesium, usually by the action of magnesium-rich brines. Minor amounts of dolomite form by direct precipitation from calcium-magnesium rich shallow marine waters.

DIAGENESIS

Diagenesis refers to the processes that alter sedimentary rocks after their deposition, either by interaction between their constituents or by reaction between their constituents and the pore fluid. For carbonate sediments, diagenesis is essentially the transformation into stable calcite or dolomite. Diagenesis includes dissolution, neomorphism, replacement of unstable minerals, compaction, recrystallization, and lithification. In general, the nature of the end product of diagenesis depends on (1) the composition of the original sediments, (2) the nature of the void-filling fluid, and (3) the physical and chemical processes involved. Climate also plays an important role. In dry regions, diagenesis is slow, whereas neomorphism occurs more rapidly in humid climates, due to the abundance of fresh water.

Aragonite and Mg calcite are unstable under most enviornmental conditions and they undergo conversion to calcite by various diagenetic processes. Aragonite changes into calcite by dissolution and precipitation. Change of Mg calcite to stable calcite takes place by leaching of Mg. The exsolved Mg^{+2} form microdolomite. Observations of Quaternary and Tertiary limestones suggest that the diagenetic process from aragonite and Mg calcite is most rapid in the freshwater phreatic zone, Fig. 1. with complete stabilization taking about 5000 years; in the freshwater vadose zone stablization is slower, taking from 100,000 to 200,000 years depending on rainfall; and in the marine zone, stabilization may take place as long as three million years.

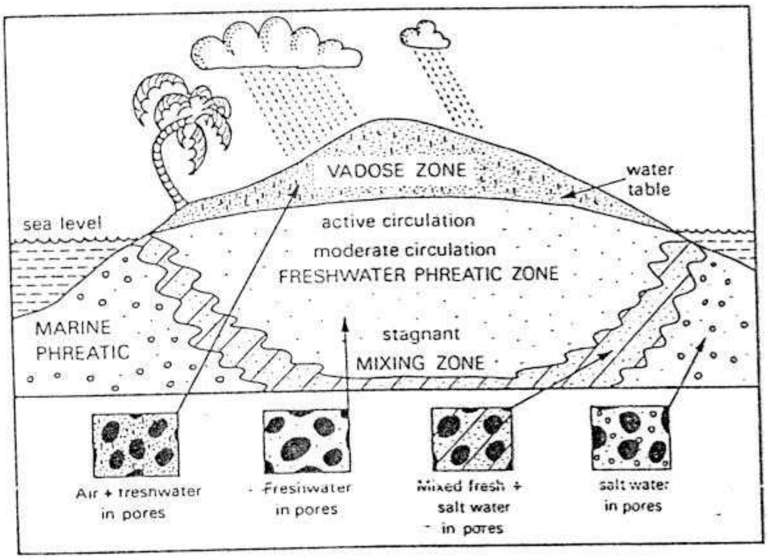

Fig. 1. **Major diagenetic environments in an ideal permeable carbonate sand island**

Dolomite often replaces aragonite and calcite. The Mg derived from the sea water is introduced into the limestone by solution passing through it. So, when calcite alters to dolomite by the reaction

$$2CaCO_3 + Mg^{+2} \longrightarrow Ca\,Mg\,(CO_3)_2 + Ca$$

there is a 12.5% decease in mineral volume and consequently an increase in porosity. Mineral replacement also involves an increase in mineral volume. Such a situation occurs during the replacement of calcite by anhydrite (25% increase in mineral volume). Aragonite to calcite transformation involves about 8% volume increase which results in porosity decrease. Anhydrite to gypsum involves 63% volume increase, causing beds to be deformed during this alteration.

Other common replacement minerals in carbonate rocks are chert, phosphorites, and siderite ($FeCO_3$). Chert commonly occurs as nodules in limestone. Siderite is common in calcareous concretions in shales, especially those of freshwater origin, Simonson (1985).

WEATHERING

Land areas are continually being reduced and their shapes modified by weathering and erosion. The susceptibility of rocks to weathering depends upon their composition.

Mechanical disintigration breaks down rocks into fragments by the action of water, wind, change in temperature, and human-activities.

Biological weathering refers to the mechanical and chemical changes that are directly associated with the activities of plants and animals. Some bacteria, for example, contribute to the making of sulphides, others can convert nitrogen into NH4 compounds which affect the PH value of the environment.

Chemical decomposition is the breakdown of minerals into new components by means of chemical agents, such as carbon dioxide, water, oxygen, and organic acids. The chemical weathering process involves: (1) reaction of the original minerals with one or more of the chemical agents to produce new minerals, and (2) dissolving of soluble minerals by water present in cracks and their eventual removal. In general, chemical weathering is promoted by high temperature and humidity. It is highly effective in warm humid regions.

The response of carbonate rocks to chemical weathering is promoted if they contain Halite (NaCl), anhydrite (CaSO4), and gypsum (CaSO4.2H2O). Dissolution of gypsum and anhydrite cause structural collapse of limestone. Thereafter, cavities would result from the rearranging of the collapsed blocks into a new rock fabric. Dissolving carbon dioxide in water produces carbonic acid which then reacts with calcite to produce soluble calcium bicarbonate,

$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2$

Such reaction results in irregular holes called vugs. Large vugs are called solution cavities. Furthermore, cavities may be produced by tensional stresses induced in response to volume changes in replacement. The tensional stresses may result in splitting the rock along surfaces to form strain cavities by dilation or rotational deformation. The cavities may be enlarged by dissolution or mechanical erosion, with undisolved and eroded fragments settle on the floors, and the remaining spaces later filled with sparry calcite.

In the Dhahran region, large-sized solution cavities were discovered during construction at three sites: KFUPM, ARAMCO, and RSAF, Fig. 2. In 1981, during excavation activities at the CIM and adjacent building sites at KFUPM, large solution cavities were found within the limestone, Fig. 3. The cavities were formed through solution of limestone by groundwater charged with atmospheric carbon dioxide, Jado and Johnson (1983). They appear to be controlld by fractures formed when the limestone slumped after dissolution of underlying anhydrite and gypsum.

In general, cavities in limestones cause problems during construction because they are not easily found in advance. Excavation may break into large cavities, which have to be filled, adding to the cost of the job. There may be cavities just below the foundations, undetected until failure occurs later.

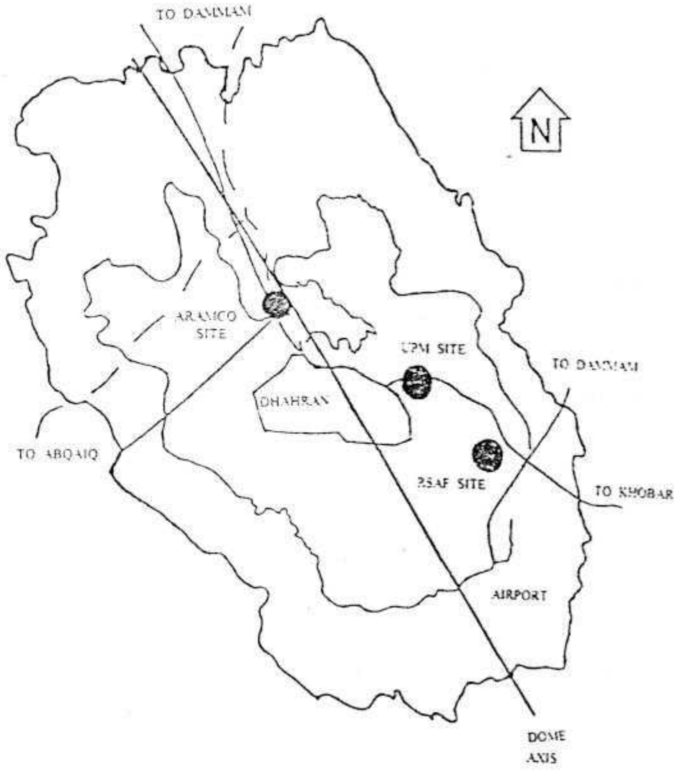

Fig. 2. Solution cavities system observed in the Dammam Dome

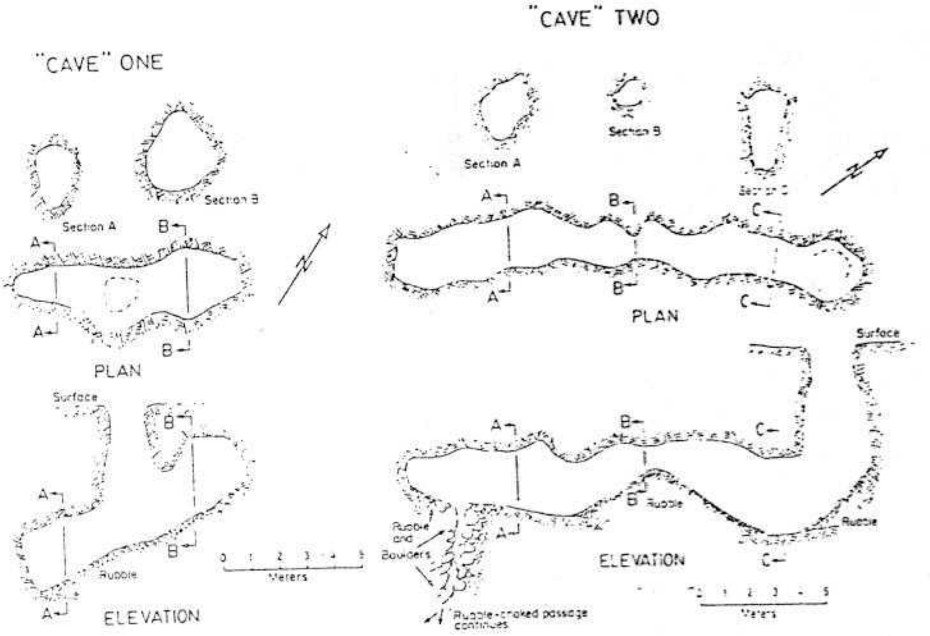

Fig. 3. Layout of cavities found in the KFUPM site

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STABILIZATION OF CALCAREOUS SEDIMENTS USING CEMENT AND STEEL SLAG AGGREGATE

Saad A. Aiban, Omar S. Baghabra Al-Amoudi,
Hamad I. Al-Abdul Wahhab and Habib-R. Ahmed

Department of Civil Engineering
King Fahd University of Petroleum and Minerals
Dhahran 31261, Saudi Arabia

ABSTRACT

Construction of roads and foundations in eastern Saudi Arabia has received special consideration from the concerned authorities due to the lack of good quality materials. Calcareous sediments, locally known as marl, are considered the best candidate for road bases and foundations in the region despite their geotechnical problems such as grain crushing, water sensitivity and inaccurate characterization procedures. The extensive use of these materials without the realization of their abnormal properties has resulted in unsatisfactory performance of many structures. Cracks in walls due to unequal settlement and subsidence of floor slabs have been noticed in few places where marls were used as a foundation or backfill material. In other places, heaving of sidewalks was observed due to the existence of expansive marls. These instances, although considered less frequent compared to those observed in roads, can cause severe damages.

This investigation is one of a series to evaluate the geotechnical properties of over twenty calcareous sediments from different places covering the eastern part of Saudi Arabia. Thereafter, two marl and one caliche soils were selected for detailed characterization and stabilization. The results indicate significant variations in the behavior of these materials whereby their strength exhibited acute water sensitivity. The addition of low cement content or steel slag aggregate improved the strength and reduced the water sensitivity significantly. The effects of cement content, curing procedure, period and temperature, and delay in compaction on the strength and durability of the cement-treated calcareous sediments were investigated. Field trials have indicated an excellent performance of the steel slag aggregate and the cement-treated calcareous sediments.

KEYWORDS

Calcareous sediments, characterization, marl, cement, steel slag, road bases, strength, water sensitivity.

INTRODUCTION

The eastern part of the Arabian Peninsula is inherited by different geological formations. It consists of Precambrian sedimentary and volcanic rocks which subsequently got metamorphosed and have intruded plutonic formations (Al-Sayari and Zotl, 1978). It is overlain by Paleozoic, Mesozoic and early Cenozoic sedimentary strata. The surface formations include consolidated sedimentary formations ranging from Paleocene to Middle Eocene age and Meocene to Pliocene age. Unconsolidated materials of Tertiary age and sediments of Quaternary age are also present. The surface formations resulted from the sedimentary shelf sea environment during which the shoreline suffered large back and forth movements. Accordingly, there exists wide variations in composition and layering.

The primary sedimentary rock formed from the calcium carbonate sedimentation is limestone. The limestone can be subsequently dolomitized and, therefore, converted to dolomite. Besides calcite and dolomite, accessory minerals such as flint, chert, and jasper are also formed. These result from a process called *metasomatism* which involves the removal of chemical constituents or the introduction of new ones, thus resulting in chemical subtraction, addition, or replacement (Challinor, 1978). It is most commonly used for the production of new minerals by the introduction of new elements from igneous sources or by percolating solutions. These processes are responsible for the formation of dolomite, chert and other minerals in calcareous soils.

The precipitation, deposition and consolidation of calcium carbonate result in the formation of limestone. The limestone undergoes mineralogical changes to form dolomite. The material formed due to simultaneous deposition of calcareous material and clay is termed marl. Marl is the main calcareous sediment predominant in eastern Saudi Arabia and used extensively in construction. There exists large differences in marl types and characteristics leading to the existence of many definitions (Aiban et al., 1997). Calcrete or calcareous duricrust also exists throughout the Shedgum area, eastern Saudi Arabia, as part of the Hofuf formation.

Construction Materials

The rapid development in eastern Saudi Arabia has led to the construction of huge industrial plants and, thus, utilization of virgin areas to build such plants and for the accompanying urbanization. The construction of foundations for different structures and highways requires the use of proper soils. The design and selection of the geomaterials for such activities should consider the local geotechnical problems and limitations and the environmental and loading conditions. Eastern Saudi Arabia has somewhat unique geotechnical properties because the soils available for construction are problematic and the loading and environmental conditions are harsh. In addition, little information is known about the abnormal characteristics of eastern Saudi soils.

The available geomaterials for constructional purposes in eastern Saudi Arabia include calcareous sediments, sands, sabkhas and expansive clays. Sands are mostly fine to medium coarse and their strength is low and does not qualify them for use under unconfined loading. Sabkhas and expansive clays are problematic but their use in some cases is unavoidable. In a special case, expansive clays can be blended with other non-expansive soils for use in lining systems and water retention structures. Calcareous sediments are considered the best available material for road bases and foundations. These materials are heterogeneous in nature and their engineering properties and performance under the local harsh environmental and loading conditions have not yet been properly researched. In addition, most of these sediments have acute water sensitivity, high grain crushing, non-plastic fines and, by definition, high carbonate content. The available classification systems and some of the standard testing procedures may not be applicable and may result in erroneous results. Among these concerns is the applicability of certain international standards in classifying and quantifying the engineering properties of these sediments. Typical examples include the grain-size distribution, especially the fine content, when comparing dry and washed sieving; the determination of liquid limit and plastic limit, realizing that distilled water is used which may cause some kind of carbonate dissolution and will definitely alter the limits and, thus, lead to erroneous classification (Aiban et al., 1995).

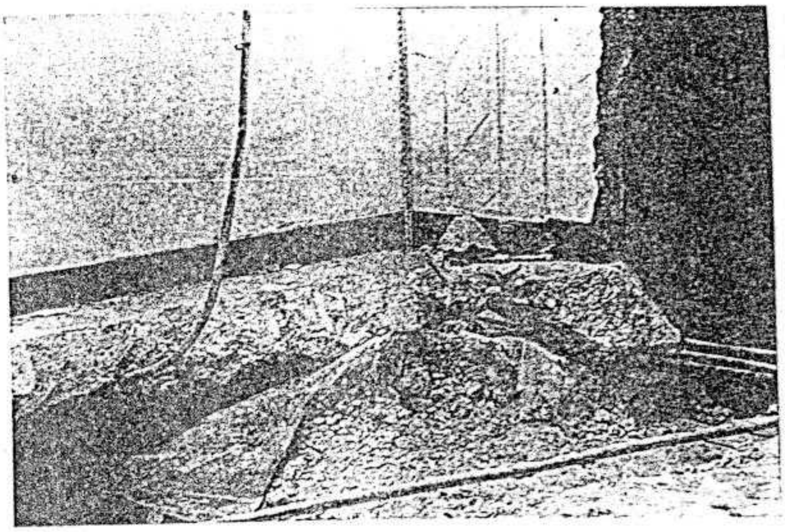

Fig. 1. Typical settlement of a concrete slab due to the collapse of the supporting marl upon flooding

The practicing engineers and researchers started realizing some of the problems associated with these soils after the occurrence of many typical problems in foundations, floor slabs and paved roads. When these fine-grained calcareous sediments are compacted on the dry side of optimum, they have some collapsing potential, mainly due to the existence of large macropores and macropeds. Thus, when the material is flooded, large volume reduction can occur and, consequently, large settlements. Fig. 1 depicts the settlement of a concrete floor slab resting on marl. The settlement exceeded 200 mm in one corner. This collapse occurred after flooding due to a leak in one of the main waterline pipes under the slab. It was found that the soil, in areas which were not flooded, is loose and is believed to be compacted on the dry side of optimum. These typical types of settlements have been observed in few places, however, little data is available because the occurrence is mostly in private properties; unlike those observed in roads.

Fig. 2. Typical deterioration of pavements when calcareous bases are used in areas with shallow groundwater table

The frequent and high rate of road deterioration in eastern Saudi Arabia when marls are used in the construction of the graded base course, has raised many concerns regarding the suitability of marl for road construction. The most important issue is the water sensitivity of the material; the strength being usually high when the material is kept dry; however, complete strength loss may result upon inundation or when the material is compacted on the wet side of optimum (Ahmed, 1996). This led to large settlements and collapse of many roads and, in many places, to complete disappearance of the asphaltic layers which become mixed with the marl base layer. An exemplary situation of such deteriorations is shown in Fig. 2. These deteriorations may take place few months only after construction. The problem usually starts with the formation of small alligator cracks that get wider due to traffic loading and flooding (if any) and divide the asphalt concrete into small blocks. These blocks displace laterally and downward and become mixed with the base layer.

EXPERIMENTAL WORK

Calcareous sediments are abundant in the Eastern Province of Saudi Arabia, however, due to the expansion and continuous growth of cities and the construction of industrial areas, quarries for aggregate for use in foundations and road bases have been allocated far from such activities. It was therefore difficult to obtain samples from all areas, however, 24 representative marl samples were collected from different locations in eastern Saudi Arabia, as shown in Fig. 3. These samples were collected from several places representing different geological formations including Abu Hadriyah, Hofuf, Abqaiq, Baggah, Dhahran, Shedgum and Ain Dar. These materials are extensively used or to be used in construction. The samples were obtained either from existing piles of soil or from crushed base course materials. Before testing, sieving of the gravel fraction was carried out and the materials retained on 2 inch (50.8 mm) sieve were excluded. The materials retained on each sieve were collected in bags and labeled accordingly. Samples for compaction and CBR tests were reconstituted according to the natural gradation of each soil or to a specific base course gradation.

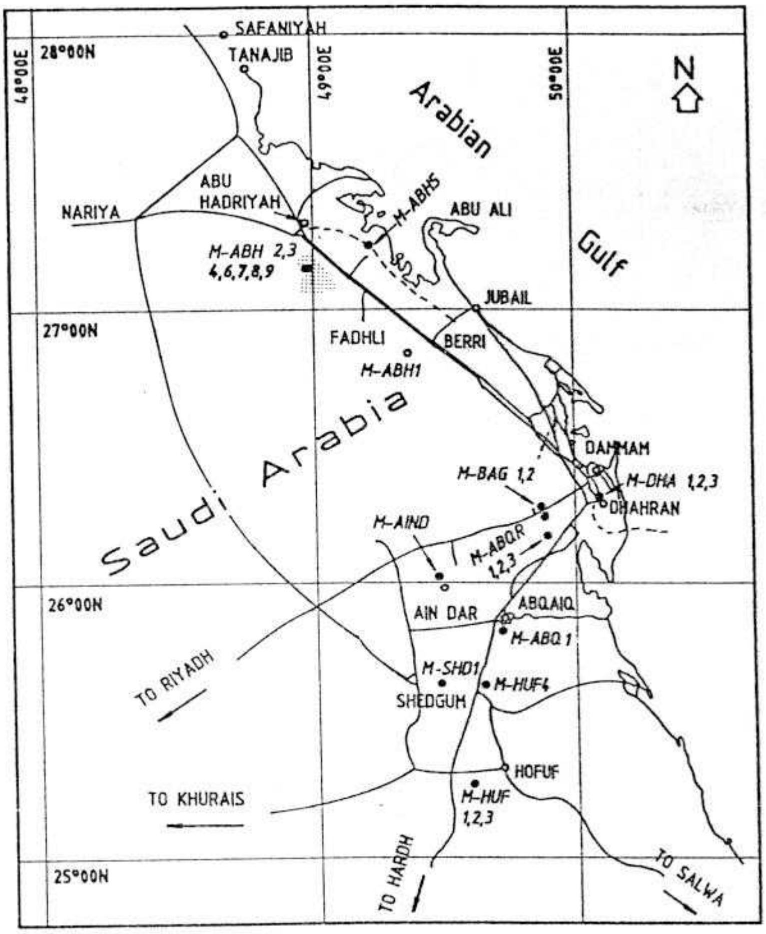

Fig. 3. Map of eastern Saudi Arabia showing sample locations

Characterization of the Collected Calcareous Sediments

Calcareous sediments have peculiar properties that are quite different from those of ordinary soils. The characteristics and engineering properties of such sediments vary greatly over a short distance. For the collected samples, the colors included white, milky, gray, yellow, brown and pink to varying degrees. These variations in colors reflect the origin and post deposition alteration and, thus, the behavior of the material. The performance of these deposits when used in construction is affected by the characteristics of the sediment including the carbonate content and origin, degree of induration, grain-size distribution, and clay type and content. The performance will also depend on the construction procedures (compaction effort, lift thickness, molding moisture content, etc.), the environmental and loading conditions, and the quality of the underlying material.

The collected samples were subjected to detailed characterization testing. Table 1 summarizes the range of values for the measured parameters. The data presented show the huge variations in the characterization and composition of the materials; even though some samples were obtained from adjacent locations within the same site. Fig. 4 clearly shows the huge variations, both lateral and vertical, within one site in Dhahran. These variations will certainly affect the soil description, classification and, more importantly, the engineering properties. The difference in fine content, when comparing wet and dry sieving for the same sample, can result

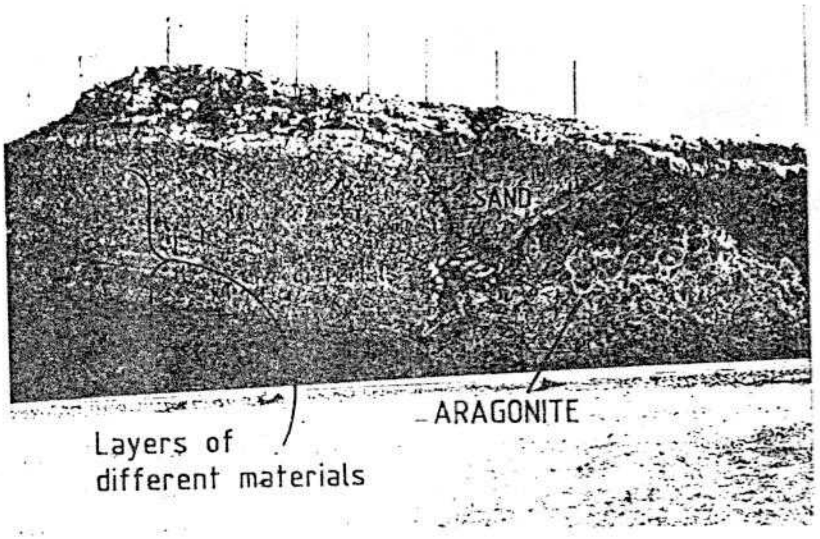

Fig. 4. Typical layering and heterogeneity of calcareous sediments

in misleading conclusions regarding the usability of the material for construction when the gradation limits on the fine content are applied. The use of dry sieving can qualify the material which, in fact, has high percentage of fines and will ultimately increase its moisture sensitivity and reduce the strength.

Mechanical Properties of Eastern Saudi Marls

The USCS and AASHTO classifications usually provide an idea about the expected behavior of the soil. As an example, A-1-a and A-1-b soils in the AASHTO classification system and some of their equivalent soils in the USCS system (GW, GP and GM, etc.) are considered the best materials for use in road bases. However, it has been observed that such classifications are of limited use when dealing with calcareous materials (Netterberg, 1982; Ahmed, 1996). This was also verified for the twenty-four marls tested here. CBR test results indicate that most of these marls are sensitive to moisture and, therefore, their usage in road construction may raise concerns even when the material is classified as an A-1-a or A-1-b soil.

Typical CBR and compaction test results are presented in Fig. 5. The sensitivity of this calcareous material to moisture content is indicated by the reduction of the CBR values when the moisture content decreases below or increases above the optimum moisture content. Severe CBR reduction (from 134 to 45) resulted when the moisture content increased from 6.4 to 7.7% which corresponds to 95% relative compaction. Moreover, a reduction in the CBR from 117 to 50 resulted due to soaking if the material is compacted on the dry side of optimum at a moisture content corresponding to 95% relative compaction. Such behavior was observed for all marl samples. The 95% relative compaction is usually accepted for road bases, however, with such low CBR (less than 50), a control of the moisture content during compaction is undoubtedly essential.

A summary of the compaction and CBR test results is presented in Table 2. It is clear from these values that the maximum CBR values occur at moisture contents lower than those for the maximum dry density (i.e. little on the dry side of optimum). In addition, for most samples,

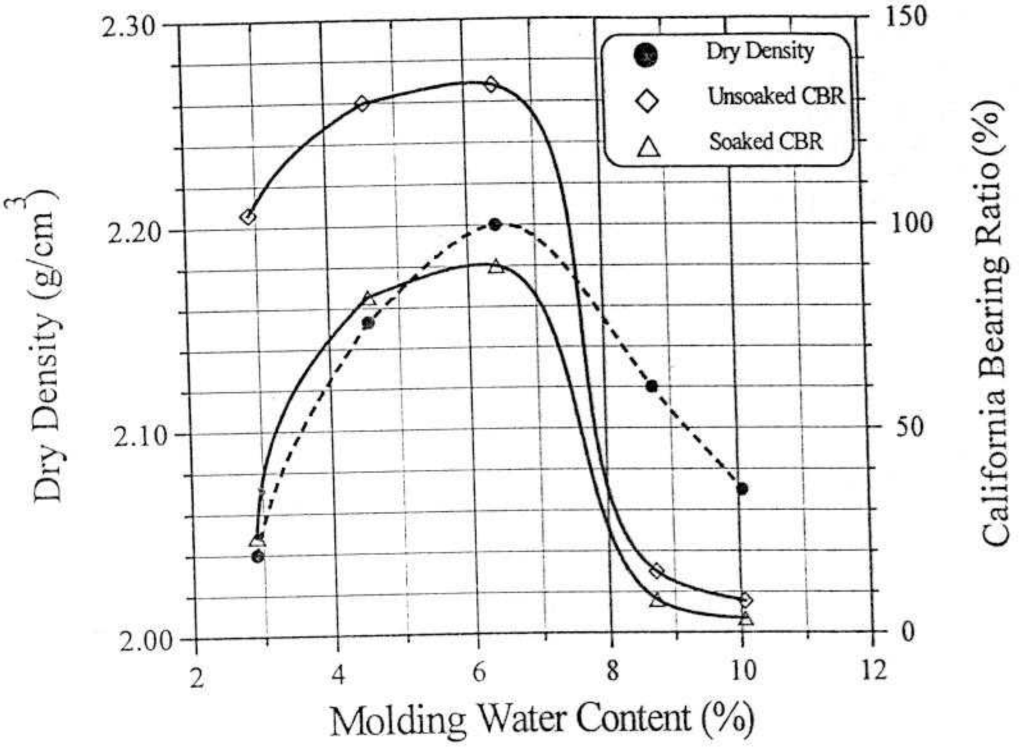

Fig. 5. Typical variations of dry density and CBR values with moisture content for Abu Hadriyah marl

the CBR and dry density values corresponding to 95% relative compaction could not be determined. This is mainly due to the difficulty in preparing samples at these moisture contents. It is also noticed that the CBR values, for samples compacted on the wet side of optimum to 95% of the maximum dry density, are very low, indicating severe strength loss. This indicates the acute water sensitivity of the material and the irrelevance of the standards imposing 95% relative compaction as a criterion at its corresponding moisture content. This encouraged further investigation and stabilization of some of these calcareous sediments.

Stabilization of the Selected Soils

The results presented in Tables 1 and 2 indicate the large variation in the behavior of marl soils in terms of gradation, plasticity, moisture sensitivity, and CBR. The poor quality of most of the eastern Saudi marls combined with the harsh loading and environmental conditions necessitate the improvement of marls when used as a graded base for roads, particularly in areas where there is a potential for water flooding. Three calcareous soils were selected for detailed characterization and stabilization; two marls, namely M-ABH9 (from Abu Hadriyah) and M-ABQR3 (from Abqaiq area), and one caliche, namely M-SHD1 (from Shedgum area), which were selected to represent different marl types and of potential use in construction.

Due to the water sensitivity of these soils, which results in a severe reduction in strength, many failure cases have been reported, most of which are in roads (Al-Abdul Wahhab and Ramadhan, 1990; Farwana and Majidzadeh, 1988; Aiban, 1995; Aiban et al., 1997). There were few attempts in the past to stabilize these materials and to improve their engineering properties. Additives, such as sand, asphalt and cement, were investigated on very limited bases. Recent studies reported by Aiban et al. (1997) showed that cement is the best chemical additive in improving the properties of eastern Saudi marls. The three selected soils were treated with different percentages of Portland cement and the effects of temperature, curing period and type were investigated. In addition, a typical marl from Abu Hadriyah area was blended with steel slag aggregate (SSA) and the effects on the CBR and water sensitivity were studied.

Laboratory Testing for Strength and Durability

Due to the acute water sensitivity which results in a severe strength reduction, more emphasis was placed on these two issues, keeping other factors such as durability and volume stability in mind. The unconfined compressive test (q_u) and the CBR tests were adopted and used for the evaluation of the strength characteristics of both treated and untreated mixtures. The CBR test was performed on all samples prepared for compaction curves. Samples treated with Portland cement were allowed to air cure for one day in the laboratory and then soaked in water for six more days. Fig. 6 shows the variation of the CBR values with cement content for the three soils. The CBR results show clearly that the CBR increased significantly with

Table 1. Range of values for characterization parameters and chemical analysis for eastern Saudi calcareous sediments

Parameter	Range of Values
Specific gravity	2.66 to 2.92
LL for material passing sieve No. 40	ND to 95.2
LL for material passing sieve No. 100	ND to 123.1
PL for material passing sieve No. 40	ND to 66.4
PL for material passing sieve No. 100	ND to 90.0
PI for material passing sieve No. 40	Non-plastic to 39.2
PI for material passing sieve No. 100	Non-plastic to 42
Passing sieve No. 200, dry sieving (%)	0.2 to 18.9
Passing sieve No. 200, wet sieving (%)	9.6 to 44.4
Classification (USCS)	SP-SM to GW
Classification (AASHTO)	A-2-7 to A-1
Calcite content for material passing sieve No. 40 (%)*	0 to 96
Calcite content for material passing sieve No. 100 (%)*	0 to 90
Dolomite content for material passing sieve No. 40 (%)*	0 to 97
Dolomite content for material passing sieve No. 100 (%)*	0 to 97
Quartz content for material passing sieve No. 40 (%)*	0 to 72
Quartz content for material passing sieve No. 100 (%)*	0 to 57

ND: Could not be determined

*from XRD analysis

increasing the cement content up to 5%. Further increase in cement content thereafter did not bring about any significant increase in the CBR values except for M-ABQR3 marl. The q_u test was performed on cylindrical specimens having a diameter of 100 mm and a height to diameter ratio (h/d) of 2. All samples were reconstituted to meet the base course gradation requirements. The required cement content and the corresponding (optimum value) moisture were added and mixed in a mechanical mixer for 4 min. For the q_u tests, the mix was compacted to the maximum dry density based on the modified Proctor compaction test in 5 equal layers. The number of blows was adjusted to attain the maximum dry density at the optimum moisture content.

Table 2. Summary of compaction and CBR test results on eastern Saudi calcareous sediments

Marl origin	Marl symbol	Max. Dry Density $(\gamma_d)_{max}$ (g/cm^3)	Optimum Moisture Content (OMC) (%)	CBR			Maximum CBR	
				at 0.95$(\gamma_d)_{max}$ (dry side)	at $(\gamma_d)_{max}$	at 0.95$(\gamma_d)_{max}$ (wet side)	CBR	moisture content (%)
Abu Hadriyah	M-ABH1	1.85	13.00	110.0	104.4	0.0	130.0	11.0
Abu Hadriyah	M-ABH2	2.09	7.25	100.0	130.0	0.0	140.0	6.8
Abu Hadriyah	M-ABH3	1.93	10.25	ND	130.0	ND	130.0	9.0
Abu Hadriyah	M-ABH4	2.15*	8.00**	ND	180	ND	180.0	8.0
Abu Hadriyah	M-ABH5	1.91	14.10	ND	122.0	2.0	152.0	12.9
Abu Hadriyah	M-ABH6	2.17	6.80	123.0	145.0	10.0	163.0	6.4
Abu Hadriyah	M-ABH7	1.80	16.65	ND	79.0	6.0	90.0*	14.5*
Abu Hadriyah	M-ABH8	1.93	12.00	ND	135.0	ND	197.0	8.0
Abu Hadriyah	M-ABH9	2.20	6.40	115.0	135.0	10.0	135.0	6.4
Abqaiq	M-ABQ1	1.85	14.00	90.0	155.0	ND	155.0	14.0
Abqaiq Road	M-ABQR1	1.81	15.00	ND	180.0	50.0	180.0	15.0
Abqaiq Road	M-ABQR2	1.79	14.90	88.8	148.4	35.0	155.0	13.5
Abqaiq Road	M-ABQR3	2.06	8.60	ND	50.0	ND	128.0	7.0
Ain Dar	M-AIND	1.87	13.50	70.0	130.0	ND	141.0	12.5
Bagah West	M-BAG1	1.69	18.61	ND	81.0	36.0	82.0	20.9
Bagah East	M-BAG2	1.79	17.50	ND	125.0	40.5	142.0	16.5
Dhahran	M-DHA1	1.75	16.00	100.0	107.0	28.0	108.0	14.0
Dhahran	M-DHA2	1.51	21.84	ND	45.0	20.0	73.0*	17.8.0*
Dhahran	M-DHA3	1.97	12.56	ND	111.9	17.5	250.0	11.0
Hofuf	M-HOF1	2.20	6.78	ND	204.5	ND	204.5	6.8
Hofuf	M-HOF2	2.07	8.50	ND	165.0	8.0	165.0	8.5
Hofuf	M-HOF3	1.67	18.53	ND	87.6	22.0	92.0	20.0
Hofuf	M-HOF4	1.94	12.40	85.0	65.0	10.0	125.0	11.0
Shedgum	M-SHD1	2.11	9.00	ND	160.0	20.0	210.0	7.0

ND : could not be detemined * no optimum was obtained ** one for maximum CBR

Samples for q_u test were allowed to cure for varying periods either at room temperature (21 ± 2 °C) or in the oven at higher temperatures. In order to simulate field conditions, some of the compacted samples were sealed in plastic sheets to inhibit moisture loss while the others were left exposed. The variation in q_u with cement content for the samples cured at room temperature for 7 days, is presented in Fig. 7 for the three soils. The results reveal that the strength of exposed samples is higher than that of the sealed ones, irrespective of the cement

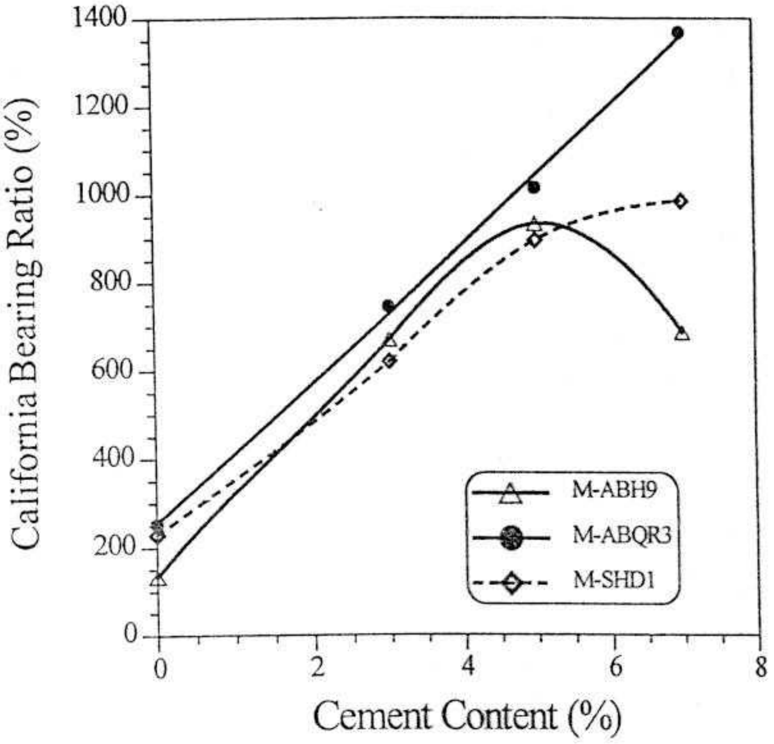

Fig. 6. Variations of CBR values with cement content for the three marl soils after 7 days of curing

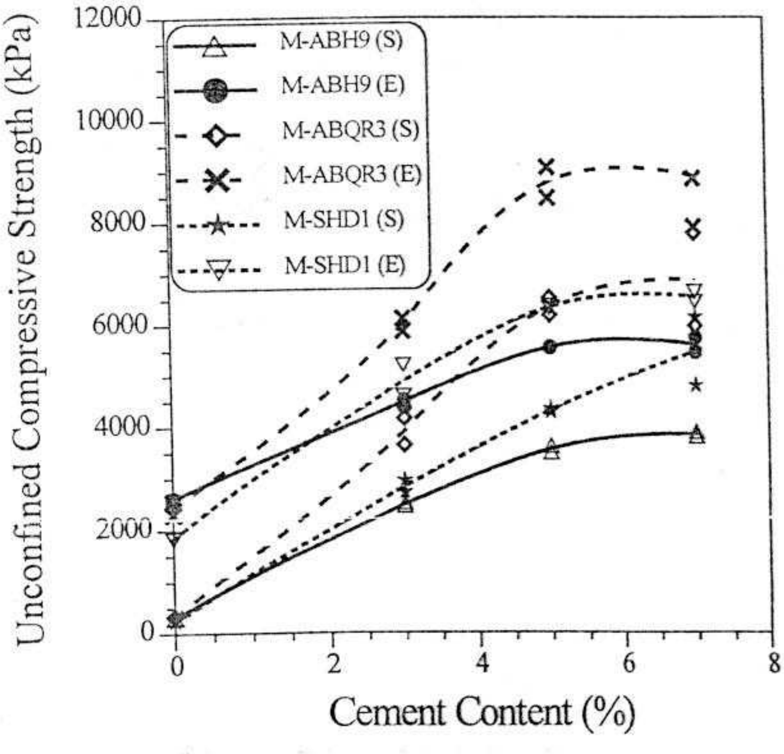

Fig. 7. Variations of q_u values with cement content for the three marl soils after 7 days of curing

content. Moreover, the strength increases as the cement content increases from 0 to 5%. Further increase in cement content did not bring about any significant increase in q_u. The average (between sealed and exposed curing) q_u for each of the three marls can be considered representative of field situations. Further, a factor of 1.10 is to be used to get the corrected q_u for the height to diameter (*h*/*d*) ratio of 1.15. This results in q_u values of 5015 kPa (730 psi), 7590 (1100 psi) and 5864 kPa (850 psi) for M-ABH9, M-ABQR3 and M-SHD1 marl soils, respectively. According to the ACI Committee 230 report (1990), the minimum q_u specified by the US Army Corps of Engineers (USACE) for base course construction is 5175 kPa (750 psi). Therefore, the requirement for q_u is fulfilled at a cement content of 4 to 5%.

The soil-cement mixtures fulfilling the minimum strength requirement should also be durable against wetting and drying. For the local environmental conditions, there is no need to investigate the durability against freezing and thawing. Both the standard test (ASTM D 559) and the modified slake durability test (Aiban et al. 1997) were conducted on soil-cement mixtures having 3, 5 and 7% cement contents. The results in Table 3 indicate that the maximum weight loss did not exceed 3%, for the 3% cement addition, and as the cement content increases the weight loss decreases. In addition, the results indicate a good correlation between the proposed procedure and the ASTM D 559 standard. The maximum allowable weight loss is 14% and 9% according to the Portland Cement Association (PCA) and US Army Corps of Engineers (USACE), respectively, which indicates that all stabilized marls are durable.

Table 3. Summary of durability test results on cement-treated calcareous soils

Material	% Cement	Weight Loss*	
		ASTM D 559	Slake Durability
M-ABH9	3	1.6	2.37
M-ABH9	5	0.66	0.63
M-ABH9	7	0.46	0.54
M-SHD1	3	2.54	2.67
M-SHD1	5	1.0	1.02
M-SHD1	7	0.91	0.90

*Average of two values

In addition to chemical additives, granular admixtures were also used in this investigation. Steel slag aggregate (SSA) has been used with one marl from Abu Hadriyah area. The SSA was added to the marl in different percentages. It was found that the marl type and content and gradation of the SSA affect the strength and water sensitivity of the mixtures. Fig. 8 shows the variation of the CBR values for Abu Hadriyah marl blended with SSA. These high CBR values are mainly due to the sound SSA. It is worth mentioning that the SSA alone can be used for base courses. Fig. 8 shows the CBR values for SSA reconstituted to an optimized gradation (Aiban and Al-Abdul Wahhab, 1997). The CBR values for pure SSA can easily exceed 300; such a value can improve the performance of roads and reduce the thickness of the asphalt concrete. It is clearly shown that the CBR values are almost twice those for the marl alone. In addition, the moisture content is not an issue since the minimum CBR is much higher than the values recommended by the local and international standards for road bases.

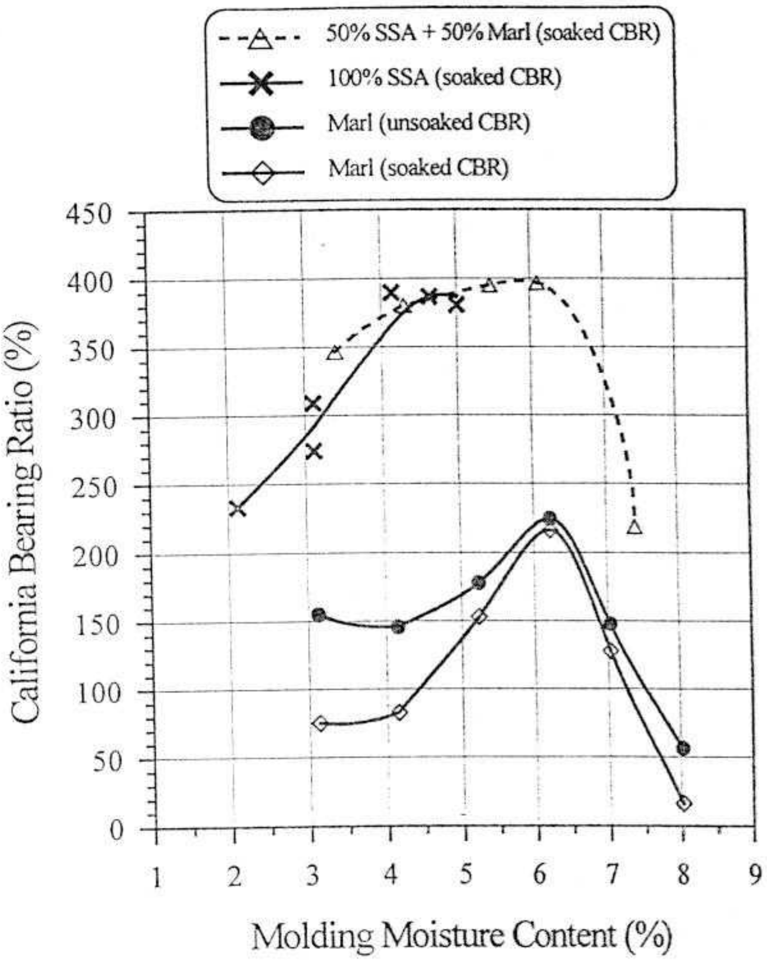

Fig. 8. Variation of CBR values with moisture content for SSA and Abu Hadriyah marl

Field Trials

The low performance of the available calcareous materials when used in construction, combined with the promising laboratory results obtained for cement-stabilized marls and SSA, encouraged the construction of field trials utilizing poor as well as good quality materials. Two field trials were constructed in regions exposed to the worst loading conditions in eastern Saudi Arabia; in the Dammam Industrial Area. In the first trial, 4% cement-stabilized Abu Hadriyah marl was used as a base course having a thickness of 200 mm. A control section was made adjacent to the cement-treated section where both sections are exposed to the same traffic. Both sections have 110 mm asphalt concrete. The cement-stabilized (treated) section exhibited an excellent performance over the past three years while the untreated (control) section deteriorated completely within few months.

In the second trial, SSA was used in the same area but at a different street. The section consisted of 100 mm fine slag aggregate (0-5 mm) overlain by 200 mm coarse SSA (0-37 mm) with the optimized gradation and having the CBR values shown in Fig. 8. The asphalt concrete for the section was 110 mm thick. The road has been in service for the past six months and exhibited an excellent performance so far. Both the cement-stabilized section and the section utilizing SSA are subjected to a periodical monitoring and testing. Further details are reported elsewhere (Aiban et al., 1997; Aiban and Al-Abdul Wahhab, 1997).

SUMMARY AND CONCLUSIONS

Results of both laboratory and field investigations reveal the significant variability and acute water sensitivity of the fine-grained calcareous "marl" sediments in eastern Saudi Arabia in their natural state. The variability was demonstrated by the characterization and composition of the materials, while the water sensitivity was typified by the significant reduction in CBR values upon wetting and its dependency on the molding moisture content. Therefore, the use of marl in base-course construction of roads under excessive loading and severe exposure conditions is questionable. Accordingly, these local materials can be upgraded efficiently once they are treated with small percentages (4 to 5%) of Portland cement or blended with SSA. Cement-stabilized road section showed an excellent performance under harsh exposure and loading conditions for three years. Similarly, the use of SSA as a partial or full replacement of the conventional aggregate for road base has shown great improvement when compared to crushed calcareous bases. The SSA and SSA-marl mixes have produced a base course that is water-insensitive with very high CBR values.

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